VULCANISM AND MOUNTAIN-MAKING: A SUPPLEMENTARY NOTE

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In a recent paper on "The Building of the Colorado Rockies,"[1] the writer compared and contrasted the Rocky Mountains of Colorado, an example of a thick-shelled range, with the Pennsylvania Appalachians, which belong to the thin-shelled type. One of the striking differences developed was that the building of the more deeply rooted Colorado mountains was accompanied by the extrusion of much lava, while the shallower Appalachians were formed with the extrusion of but little lava. A further comparison was made between different portions of the Rocky Mountain chain itself. In Colorado, where the deformed zone extended deep below the surface and the vertical element in the deformation was distinctly large, lava flows appeared in abundance; while in the Canadian Rockies, where the deformed zone was much shallower and suffered intense horizontal thrust, but very little volcanic activity occurred.

The study was really concerned with only these ranges, but some of the ideas developed were extended, as tentative suggestions, to other mountain systems. The Alps, the Scandinavian chain, the Scottish Highlands, and the Serra do Espinhaço of Brazil were cited as probably belonging to the thin-shelled type because of their sharp folding, extensive thrust faulting, and great crustal shortening, and it was stated that "only moderate igneous activity" was associated with their development.[2] As representatives of the

[1] *Jour. Geol.*, Vol. XXVII (1919), pp. 248–51.

[2] This refers only to the strongly deformed portions of these ranges, since any igneous manifestations outside of these belts would also be outside the thin-shelled tracts, even though they be more or less related genetically to the mountain-making stresses. In the case of the Alps, the statement refers of course to the intense Tertiary diastrophism. Whatever relation the granites in the axial portions of the Alpine ranges may have had to the Hercynian and earlier orogenic movements is not here considered.

thicker-shell type of mountains in which vertical movements are more pronounced and horizontal thrusting and shortening less conspicuous, the Tertiary Cascades of the Pacific Coast, the Western Andes, and the Abyssinian Mountains were cited. In contrast with the preceding, the growth of these ranges was marked by the extravasation of vast floods of lava.

In this treatment of the subject it was not explicitly stated that extrusive vulcanism alone was considered, although the text would seem to the writer to convey that idea clearly enough. In view of the fact that intrusions did not enter vitally into the Appalachian section of Pennsylvania or that of the Colorado Rockies,[1] this phase of vulcanism had no place in those studies, and so the topic of intrusions was not introduced into the comparison of thin-shelled and thick-shelled ranges in general. But there are, however, certain cases in which plutonic rocks appear in ranges of the thin-shelled type in such a way as to suggest that intrusions on a large scale may be a common habit of this type. It is because of the feeling that the absence of any statement covering the intrusive phase of vulcanism might convey erroneous ideas, and perhaps lead to more or less justified criticism, that the present note is added.

Many folded mountain ranges of both thin-shelled and thick-shelled types are characterized by cores of crystalline rock, in considerable part of igneous origin. In many of these the crystalline rock clearly belongs to an old terrane arched up in the folding process and exposed by erosion; but in many other cases the intrusive relations of the igneous rock lead to the belief that it was intruded into the axis of the folded range in a late stage of the arching process. The wide prevalence of this phenomenon has been emphasized by Daly in the following terms:

> Granitic intrusion of the batholithic order, to observed levels, always follows periods of the more intense orogenic movement. This implies that the greatest abyssal injections of the earth's crust by magma are genetically associated with the horizontal shearing of a superficial earth-shell which is much thinner than the whole crust.[2]

[1] Except in the pre-Cambrian complex, which has nothing to do with the Rocky Mountain diastrophism.

[2] Reginald A. Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Geol. Surv. of Canada, Mem. 38,* Part II (1912), p. 573.

Cores of granodiorite and allied rocks having intrusive relations with the adjacent sedimentaries are very conspicuous in the sharply compressed Sierra Nevada Range, the Mesozoic Cascades, the Coast Range of British Columbia, and various members of the Cordilleran chain extending into Alaska—a group folded, according to present information, at about the close of the Jurassic. Throughout this disturbed region the Jurasside batholiths are a dominant feature.

In some of these cases, at least, the intrusions seem to follow in consequence of the folding, and to appear beneath the most strongly arched portions of the ranges, presumably in consequence of reduced pressure. That the arching process tends to relieve the pressure beneath and hence favors liquefaction and the penetration of magmas, is a principle long recognized and variously utilized in explaining vulcanism.[1] But whether the arching and partial relief of pressure be a major or a minor factor in the actual liquefaction of the magma, the shearing movements involved in this type of deformation might well facilitate the transfer of magma, and would favor its insinuation near the surface, either as irregular batholithic bodies, or perhaps more likely as large lenticular or pancake-shaped intrusive masses whose thicknesses are much less than their horizontal extent. The general laccolithic shape, using the term in its broadest sense, would seem to be the favorite form.[2] Intrusions of this sort occur in both thin-shelled and thick-shelled ranges.

THIN-SHELLED TYPE

In those thin-shelled ranges in which overthrust faulting has been a dominant feature, intrusions formed in this way should not be conspicuous in the marginal portions where the phenomena of overthrusting are best displayed and the shell was thinnest, but rather in the heart of the deformed belt, where the shell involved in

[1] W. Hopkins, "Researches in Physical Geology," *Phil. Trans.*, Part I (1842), pp. 43–55; Eduard Suess, *The Face of the Earth*, Vol. I (1904), p. 170; W. H. Hobbs, "Some Considerations Concerning the Place and Origin of Lava Maculae," *Beiträge zur Geophysik*, Vol. XII (1913), pp. 329–61.

[2] W. C. Broegger, *Eruptivgesteine des Kristianiagebietes*, II (1895), pp. 116–53; Alfred Harker, *The Natural History of Igneous Rocks* (1909), pp. 60–87.

the diastrophism went somewhat deeper and lifting was relatively more important. As a part of the Jurasside orogeny which developed the Sierra Nevada Range, powerful overthrusting occurred far to the east of these mountains.[1] But in these areas of overthrusting igneous activity contemporaneous with the diastrophism seems to have been unimportant.

The extraordinary Caledonian diastrophism affected both the British Isles and Scandinavia. In the Scottish Highlands on the western border the planes of overthrusting dip eastward under the deformed belt; in Scandinavia they dip westward likewise beneath the strongly deformed belt. Singly, each case illustrates the principle of bordering thrust faults on the outer margins of compressed mountain ranges.[2] Together, Scottish thrusts on the west and Scandinavian thrusts on the east, they constitute seemingly a wedge similar to the Appalachian wedge of Pennsylvania.[3]

The region of these extraordinary Caledonian overthrusts in the Northwest Highlands of Scotland seems to have been essentially free from igneous phenomena during the time of the vigorous deformation.[4] Such intrusions as took place at this time were located off to the southeast, especially in the Ochil and Sidlaw Hills[5] and the Cheviot district, which are near the middle of the deformed belt far from the overthrust border. During the deposition of the Lower Old Red Sandstone which followed the Caledonian disturbance, large quantities of volcanics were poured out in the central Lowlands between the base of the Highland Mountains and the Uplands of the southern counties.[6] But no undoubted vents of Lower Old Red Sandstone age have been detected

[1] C. R. Longwell, "Geology of the Muddy Mountains, Nevada, with a Section to the Grand Wash Cliffs in Western Arizona," *Am. Jour. Sci.*, Fifth Series, Vol. I (1921), pp. 39–62; E. S. Bastin, personal communication.

[2] "The Building of the Colorado Rockies," *Jour. of Geol.*, Vol. XXVIII (1910), pp. 243, 249.

[3] Rollin T. Chamberlin, "The Appalachian Folds of Central Pennsylvania," *Jour. of Geol.*, Vol. XVIII (1910), pp. 228–51.

[4] "The Geological Structure of the Northwest Highlands of Scotland," *Mem. Geol. Surv. of Great Britain* (1907).

[5] Sir Archibald Geikie, *Ancient Volcanoes of Great Britain*, Vol. I (1897), pp. 277–79.

[6] *Ibid.*, pp. 271–72; 295–335.

among either the Highlands on the one hand or the Silurian Uplands on the other.[1]

In Scandinavia the deformed igneous masses resting upon the Cambro-Silurian sedimentaries in the Caledonian mountain belt have been regarded by Törnebohm as portions of the Archean brought from the west by the overthrusting process.[2] If so, contemporaneous intrusions played little part in the overthrust sheets. According to Holtedahl, however, the gneisses are to be regarded as highly pressed younger intrusive masses which, during the deformation, broke forth and moved under enormous pressure from the central belt outward.[3] If in truth these be intrusions related to the Caledonian diastrophism, they are in any case more characteristic of the central belt than of the outer borders.

Among the intensely deformed Cenozoic Alps intrusions of Tertiary age are practically wanting in the central and northern ranges which together make up the region of the *nappes de charriage*, or great overthrust sheets. But in the root region of the Lepontine sheet and the Dinaric zone on the south side of the Alps, from which the overthrust masses are thought to have come, the last phase of strong mountain-building was characterized at various points by intrusions of a granitic nature.[4] Steinmann has already emphasized this contrast between the region of the roots and the region of the sheets.

In addition, it is of course to be noted that quite outside of the true mountainous belt, particularly opposite the inner curves of the arcuate chain (in Hungary, Italy, etc.), volcanic phenomena attained considerable prominence.[5] But the more or less contemporaneous extra-montane vulcanism, though related to the mountain-building stresses, is not a part of this discussion.

[1] Sir Archibald Geikie, *Ancient Volcanoes of Great Britain*, Vol. I (1897), p. 272.

[2] A. E. Törnebohm, "Grunddragen af det Centrala Skandinaviens Berbyggnad," *Kongl. Svenska Vet.-Akad. Handl.*, Vol. XXVIII (Stockholm, 1896), pp. 1–210.

[3] Olaf Holtedahl, "Paleogeography and Diastrophism in the Atlantic-Arctic Region during Paleozoic Time," *Am. Jour. Sci.*, Vol. XLIX (1920), pp. 1–25.

[4] G. Steinmann, "Die Bedeutung der jüngeren Granite in den Alpen," *Hauptversammlung der geol. Vereinigung*, Frankfort (1913), pp. 1–4.

[5] Marcel Bertrand, "Sur la distribution géographique des roches éruptives en Europe," *Bull. soc. géol. de France*, 3e sér., Vol. XVI (1887–88), pp. 573–617; Alfred Harker, *op. cit.*, pp. 20–22, 42.

The last thin-shelled range listed in the paper on the Colorado Rockies was the Serra do Espinhaço of Brazil. In the thrust-faulted portion of this ancient system very little igneous activity of any sort has occurred.[1] Eastward for 170 miles toward the Atlantic Coast, in which strip the heart of this mountain system presumably lay, there remains today only what has been called the Archean Complex. This region is characterized by many massive intrusions. Some of these may possibly have been injected at the time of the Serra do Espinhaço orogeny, though there is no evidence as yet bearing on this question.

Similarly in the Canadian Rockies very little igneous activity occurred in the overthrust region of Alberta; but farther west some of the massive intrusions in British Columbia may prove to have been related to this thrusting.

The outer marginal portions of ranges of this type, both folded and faulted, are particularly superficial. In the great overthrusts but very shallow flakes have been moved. The very low inclination of the fault planes does not carry them to great depths. Beneath the planes of overthrusting, the underlying strata, if of incompetent material, are found to be contorted in many places, but this folding rapidly dies out away from the thrust planes. Such shallow deformation does not greatly facilitate the movement of magmas. But back in the heart of the deformed belt the disturbance goes much deeper, and uplifting with relief of pressure beneath is more pronounced. Here, as the above-mentioned illustrations seem to show, intrusions tend to develop.

THICK-SHELLED TYPE

As pointed out, the thick-shelled mountains have been characterized by open, gentle folding, moderate crustal shortening affecting a deeper zone, by strong uplifting, and the extravasation of much lava.[2] Vertical diastrophism seems to dominate over horizontal. Normal faulting is an important accompaniment, occurring either incidentally as a part of the uplifting process or as a result of subsequent relaxational movements of the raised plateau-like area. Iddings has given an excellent

[1] E. C. Harder and R. T. Chamberlin, "The Geology of Central Minas Geraes, Brazil," *Jour. Geol.*, Vol. XXIII (1915), pp. 341–78.

[2] *Jour. Geol.*, Vol. XXVII (1919), p. 251.

exposition of the part block faulting has played in the extravasation of lava.[1] According to his belief, block faulting under tensile stress offers the principal outlets for the escape of lava. To quote: "The deepest fractures starting from the zone of potential magma should permit its eruption and intrusion between blocks that tend to part from one another by reason of the tensile stress." The wide prevalence of normal faulting in mountains of the thick-shelled type should therefore be an important factor in the rise of magmas. The steep inclination of normal fault planes carries these fractures to greater depths than the more gently inclined thrust faults. At the same time normal fault planes because of the governing tensile stress, at least locally, become the more ready avenues of escape for the lavas. While rhyolite and other acidic lavas have appeared in vast quantities in some places, andesitic and basaltic lavas appear to have been, on the whole, more abundant. This may perhaps be in part because the greater liquidity of the basic lavas makes migration along narrow fissures easier for them than for the more viscous silicic magmas.

SUMMARY

The formation of thick-shelled mountains is characterized in general by much volcanic activity. There may also be important intrusives bearing a close relation to the mountain-making stresses. The growth of thin-shelled mountains, on the other hand, is accompanied by very little volcanic activity, at least within the truly mountainous belt. Little igneous activity of any sort is manifested in the marginal and most strongly overthrust portions of thin-shelled ranges; but in the heart of the deformed belts, where there has been more uplifting and the affected zone goes deeper, granitic and other intrusions are a common and probably characteristic feature. It is of course also to be recognized that a region which, in an earlier age, has undergone deformation of the thin-shelled type may, in a later age, after long continued denudation, participate in orogenic movements of the thick-shelled type and so become the scene of volcanic activity on a large scale.

[1] J. P. Iddings, *The Problem of Vulcanism* ("Silliman Memorial Lectures"), Yale University Press (1914), pp. 79–81, 183–84.